

CONF-760942--20

LA-UR-76-2025

TITLE: THE STATUS OF LAMPF

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SUBMITTED TO: 1976 Proton Linear Accelerator Conference
Chalk River, Ontario, Canada
September 14-17, 1976

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THE STATUS OF LAMPF*

by

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Prologue

A schematic view of the Los Alamos Physics Facility is shown in Fig. 1.^{1,2} The facility was designed primarily as the first of the "meson factories" and has become one of the principal research tools for medium energy physics. Two separate 750-keV injectors are used to provide H^+ and H^- beams. Acceleration to 100 MeV is done in a drift tube linac which is post coupled beyond 5 MeV. From 100 to 800 MeV a side-coupled linac structure is used. The machine was a significant advance in the art of linac design with high-duty factor, new types of accelerator structure,³ and computer control⁴ as the major advances. The experimental areas are arranged so that many different experiments can use beam at the same time. The very large proton currents present unusual problems in induced radioactivity, targeting, shielding and other aspects of the beam transport systems.

The LAMPF accelerator first attained the full design energy of 800 MeV in June 1972. The experimental areas followed and by August 1973 beam was supplied to the nucleon physics area for the first intensive experimental work. The main meson area was next and by April 1974 the major portions of the facility were in use for the initial round of experiments. Operation started at 1- μA average current using an H^- beam to supply both experimental areas; the intensity was gradually increased and by December 1974 the facility was operating routinely at 13- μA average current.

During this first year of production beam was supplied to 65 different experiments with a total of 61297- μA hours of production beam. This large number of experiments gave the scientific community a good start on exploiting the use of this new facility; the large number of experiments also gave the staff valuable experience in the problems associated with providing beam to as many as eight or ten separate simultaneous experiments.

During 1974 it became very clear that some substantial revisions would have to be made to the facility before higher currents and good beam availability could be achieved. Some specific acceleration problems which were found were: the need for better cooling of the bellows assembly for the drift tube stens, improved alignment so that both H^+ and H^- beam could be used simultaneously, and the need to change one or more drift spaces along the accelerator to improve damping of phase oscillations. In the experimental area the low-current operation demonstrated the need for better shielding, collimators to protect instrumentation, improved radiation hardening of target cell components, and many other similar design improvements.

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

In January 1975 we started a major shutdown to correct the deficiencies in the facility as well as to extend its capabilities with another meson line. The basic criteria for this shutdown were that the facility must be upgraded so that it could operate at the 100- μA level with acceptable beam availability; wherever possible we should make provision for eventual 1-mA operation. For the accelerator, this work was finished by August 1975, and the machine came back on for development work. An improved switchyard permitted experimental work in the nucleon physics area in October 1975; the high-intensity beam lines were back in operation in April 1976. In essence, it appears that the minimum goals of this shutdown were achieved; it remains to be seen how difficult higher current operation shall be.

Present Operation

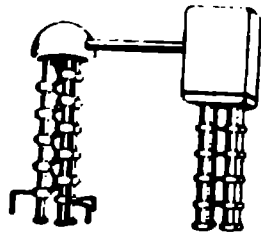
Following the shutdown we first used an H^- beam to serve the nucleon physics facility at currents of 1 to 5 μA ; when the main meson area came into operation we started dual-beam operation with an H^+ current of 10 μA . The H^+ current was gradually increased and by late summer 1976 routine operation with 100- μA H^+ current was achieved. This is with conservative beam loss along the accelerator and appropriate momentum distribution so that the beam can be deflected in the switchyard without undue problems caused by off-momentum particles. (The constraints on beam loss are discussed in more detail below.) Simultaneously, with the 100- μA H^+ beam a 1- to 3- μA H^- beam is routinely in use.

The macroscopic duty factor of both beams is 6% (500- μs pulse, 120 pps). The normal microstructure has a 5-ns period; the microstructure of the H^- beam can be changed to either a 40-ns or 80-ns period, without affecting the H^+ beam. The pulse length and repetition rate (up to 120 pps) of either beam can be varied as desired. Intensity modulation is available on the H^+ beam; in the present form every tenth pulse can be reduced in intensity by a factor of several hundred. The H^+ beam can also be deflected into a separate beam line (Line D) by a pulsed magnet; the usual rate for this deflected beam is one pps. It is possible to serve all experimental areas with the H^- beam if necessary.

During production runs since April 1976, beam availability for both the H^+ and H^- beam has averaged in excess of 80%. This availability has varied between 70% and 90% averaged over typical 14-day production periods. In view of the complexity of the accelerator and beam transport and the large number of rf systems in use these beam availabilities are quite gratifying.

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COCKCROFT-WALTON



750 keV INJECTOR

DRIFT-TUBE LINAC



201.25 MHz

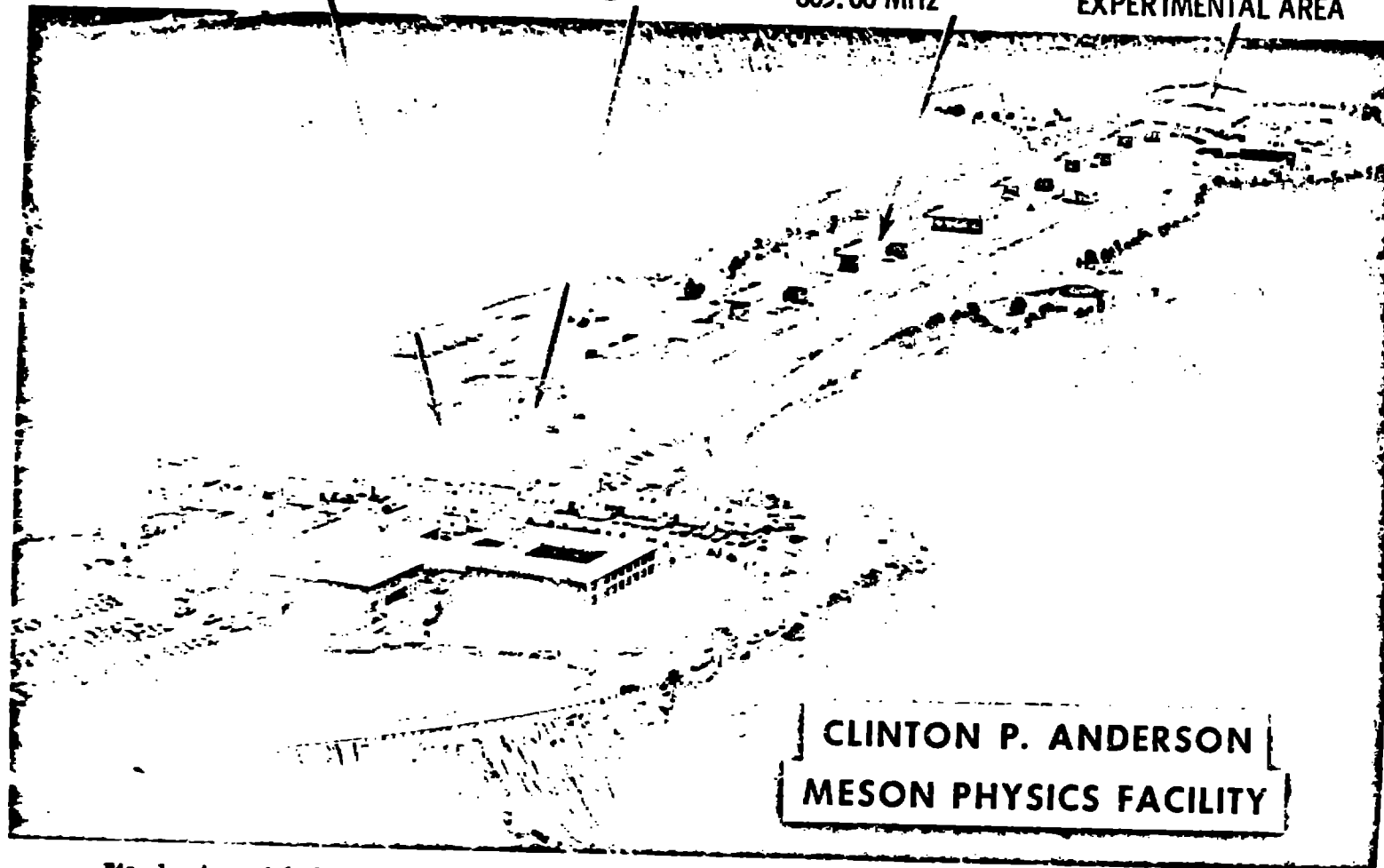
SIDE-COUPLED LINAC



805.00 MHz



EXPERIMENTAL AREA



CLINTON P. ANDERSON
MESON PHYSICS FACILITY

Fig. 1. An aerial photo of the Clinton P. Anderson Meson Physics Facility (LAMPF). The distance from the front of the office building to the far end of the experimental area (upper right) is 1.1 km.

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The causes of downtime are documented both in a detailed data base⁵ and the shift report prepared by the Chief Operator. The detailed data base provides a daily report to all interested personnel on equipment failures in the last 24 hours (or preceding weekend); this data base also provides the resource for detailed questions concerning component or system failure. The daily report has proven to be an extremely valuable method of providing the necessary communication between operating and maintenance personnel. Table I shows the leading causes of downtime from November 1975 through July 1976.

TABLE I
SUMMARY OF MACHINE DOWNTIME

	Percent of Total
201 MHz rf system	19
805 MHz rf system	18
Vacuum	11
Computer control and data acquisition	11
Injectors	7
Interlocks	7
Beam diagnostics	2
Other (water, utilities, special small systems)	25

In the design and early operation of the facility we were quite concerned about the lifetime of the large (and expensive) electron tubes⁶ which supply the rf power to the linac. Fortunately, experience has demonstrated that the lifetimes are excellent; the lifetime for the major tubes are summarized in Table II; two klystron lifetimes are shown because two different designs of these tubes are in use.

Rebuilding of large power tubes is normal practice which significantly reduces cost without compromising availability. The triodes are rebuilt by the vendor; the klystrons are rebuilt in a tube shop at LAMPF. The family of klystrons with the shorter life are rebuilt in a modified form so that the newer version of this tube should have an improved life.

In order to achieve good availability it is necessary to have skilled and dedicated operating

and maintenance personnel with appropriate scheduled maintenance periods. Detailed maintenance schedules and procedures have proven to be essential; quality control on repaired components must be maintained. Detailed tune-up procedures are equally important.⁷ This formalism is at odds with the flexibility which must be maintained in order to further develop the facility; the conflicts between production requirements and development requirements will demand compromise as long as the facility is to grow.

The stability of the machine parameters has improved enough so that production can be sustained for two weeks without significant retuning. It is not yet possible to turn the machine back on after an extensive maintenance or accelerator development period without retuning; this is a reflection of the complexity of the device, the tight tolerances on the accelerator field, and the random walk introduced by small drifts in many different subsystems.

A plan view of the experimental area is shown in Fig. 2.⁸ Our typical production periods now have four experiments in Area A at one time, two in Area B, development work using beam in Area C for the high-resolution spectrometer, an experiment at the biomedical facility, one to three experiments at the neutrino area, intermittent nuclear chemistry exposures at the beam stop, occasional development work at the isotope production area, and use of the thin target facility. Nuclear chemistry exposures are also done in Area B; line D is served as required by time sharing of the beam. Depending on the location, experiments may be changed frequently during a production period or a single experiment may receive beam for the entire run. Scheduling of the experiments is quite formal; the complexity and size of many of the experiments requires substantial engineering, mounting, fabrication, and computer support.

The H^- beam is used for Areas B and C. In Area B it is used directly or to provide a neutron beam from a deuterium on other low Z target. The wonderful ease with which H^- can be converted to H^+ by passing through a thin foil makes the H^- beam uniquely suited for applications in which very precise control of phase space is required. This property is exploited for our low-current external proton beam (Area B) and the beam for our high-resolution spectrometer (Area C).

The H^+ beam after leaving the switchyard passes through three meson production targets before

TABLE II
TUBE LIFETIMES

Tube	Frequency (MHz)	Typical Peak Power (MW)	Total Experience (Filament Hours)	Estimated Life
7835 Triode	201.25	3	66,900	9,300
Klystron	805	1	739,900	18,400
Klystron	805	1	133,900	6,000

As of June 1, 1976

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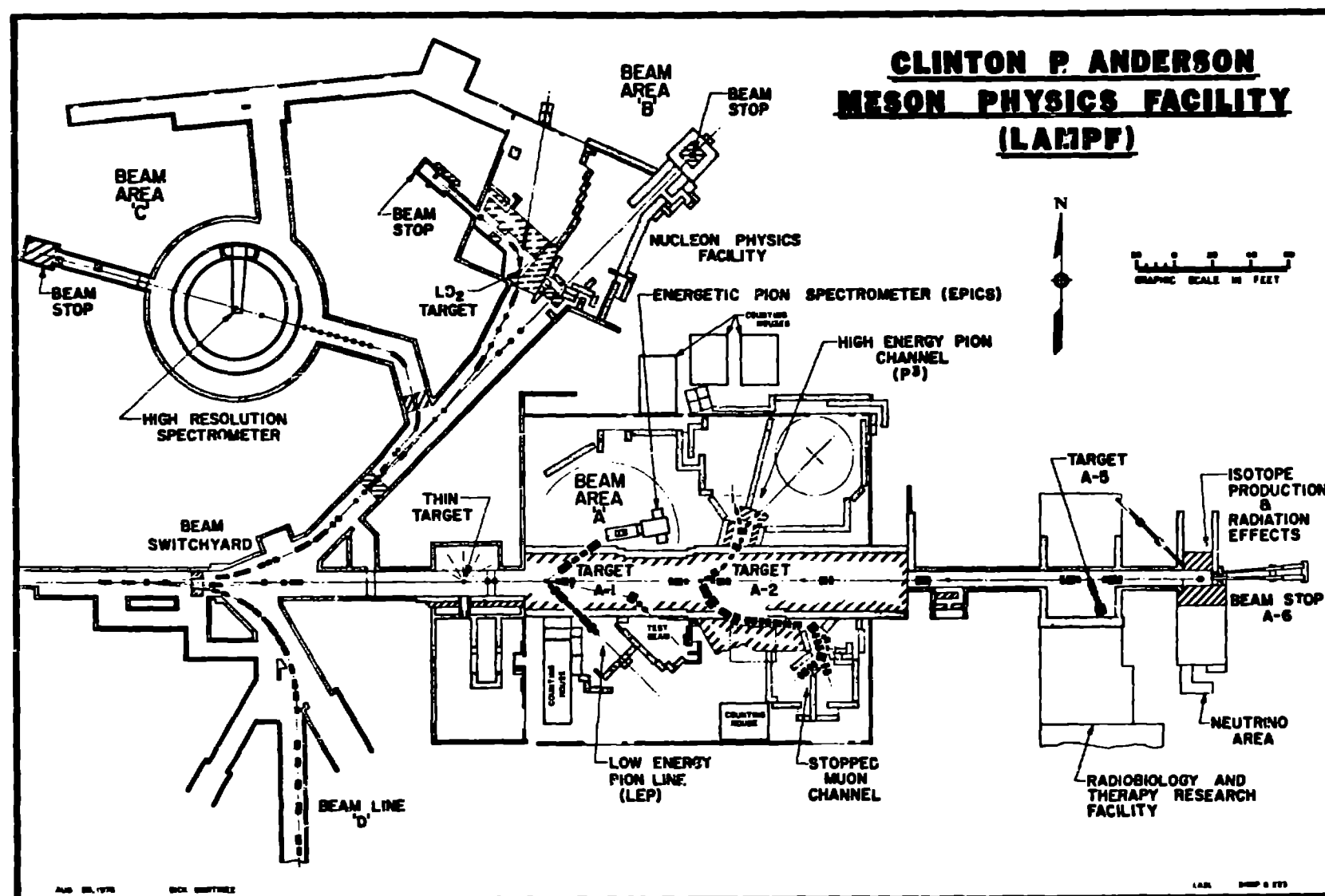


Fig. 2. Plan view of the LAMPF experimental areas. The high-intensity H^+ beam is used in Area A; the low-intensity H^- beam serves Area B and Area C. The H^+ beam is used in line D on a time-shared basis.

- reaching the isotope production facility and the beam dump area. The first target (A-1) is typically 3-cm graphite, the second (A-2) 6-cm and the third (A-5) 8-cm. After interacting with the first target the beam properties are governed by the target rather than the beam characteristics of the accelerator.

The first target provides mesons for the Energetic Pion Spectrometer Line (EPICS) and the Low Energy Pion line (LEP). The second serves the Stopped Muon Channel (SMC) and the High Energy Pion Channel (P³). The third target is for the Biomedical Channel. All of these lines are in routine operation; P³ and SMC can be switched to either of two experimental caves and a third cave is coming into use on the SMC. The pion spectrometer for EPICS is not yet complete but the channel is in use for experiments.

The use of the facility for experimental physics and practical application work has been intensive since we came back into operation; a total of 14275 h of beam (365479- μ A h) has been provided for more than 60 different experiments (as of early August 1976). Nearly all of this beam was at 800 MeV; a relatively small amount of beam time was provided at lower energies for specific experiments. Some measure of the scope of the experimental work is indicated by the fact that some 100 publications have been made directly related to the LAMPF experimental physics work. In the physics program the experimental work emphasizes questions of nuclear structure using either mesons or protons as probes; significant effort is also placed on particle physics questions. The practical application work ranges from biology studies on the effects of pions through production of isotopes to studies of radiation damage. Along with this direct practical application work there are "spin-off" studies exploring new accelerator design and applications of LAMPF-developed technology.⁹

Limitations on Current

The dominant theme of a "meson factory"¹⁰ is to produce the highest possible fluxes of particles for experimental work. The LAMPF has always had a design average current of 1 mA; it is appropriate to briefly describe some of the difficulties which must be overcome before operation at this very high current level is achieved.

The foremost problem with operation of a high-current machine is the control of induced radioactivity. In our machine only the high-current target cells and beam stop are designed for remote maintenance. The accelerator, the beam switchyard and other portions of the beam lines must be maintained either "hands on" or with only the simplest forms of remote handling (shadow shields, long wrenches and the like). Depending on the location of the beam spill thermal problems may also arise at surprisingly low levels; for example, some types of demountable, metallic vacuum seals must not receive more than a localized beam loss of 100 nA.

Along the accelerator we limit beam loss so that the average radiation level 30 cm from the "hot spots" is a few tens of mr/h shortly after turning the beam off (these hot spots are at the focusing

quadrupole doublets). The geometry of the structure is such that back a few meters the level is a few mr/h; this reduction results from both self shielding of the structure and the localized nature of the loss. This sort of activation level requires transmission through the machine at the 99% level or better (at 100- μ A average current).

Losses along the machine are caused in many different ways; some of the obvious causes are: improper steering, poor matching of the beam emittance to the focusing quadrupoles, and off-momentum components of the beam which are gradually lost radially. The steering and matching problems are further complicated by the need to have good transmission for both H⁺ and H⁻ beams.

In the switchyard beam losses are quite localized and seem to be dominated by off-momentum components which are separated from the beam line by the deflecting magnets. It is essential to limit these losses to less than 100 nA; thus at present, we cannot have more than one part in one thousand of the average current not accelerated to the operating energy. Even when losses are limited to this level one frequently has to do interim repairs in radiation fields of several hundred mr/h.

As the current is increased beyond the 100- μ A level the emittance of the beam from the ion source increases; whether or not this will be at an acceptable value at the 1-mA level remains to be seen. If not, improvements in source brightness will be required.

The fundamental problem in producing high quality beams remains the appropriate adjustment of the phase and amplitude in the bunchers and 48 separate sections of the accelerator.¹¹ Much progress has been made in finding faster and more accurate methods of setting phase and amplitudes. One of the real difficulties associated with this problem is the nonorthogonality of the many different parameters and the myriad of different set points which can produce sensibly the same beam; another difficulty is the impossibility of accurately measuring phase and amplitude of the accelerating field other than through its effect on the beam. Equally important with initial tuning to a usable set of accelerator parameters is the stability of the entire system so that the set points are maintained. As beam current is increased, further difficulties are encountered in control of phase and amplitude due to large beam loading (at full design current beam loading approaching 30% appears in some parts of the machine). This problem is particularly difficult in control of the transients at the beginning of the beam pulse.

Clearly under these conditions one must have a stringent automatic control method to limit loss. The primary method in a system of radiation detectors which are arranged so that the beam is quickly turned off whenever a preset level is exceeded. As we go up in current direct measurement of transmission is coming into use and it is required that for "beam on" the appropriate transmission level is maintained. Automatic systems which limit the beam current if excessive beam strikes a collimator or the beam location wanders unduly are also being developed.

In the main target cells and at the beam stop the induced activity problem is at its very worst. In addition, thermal problems are severe; for example with a 6-cm carbon target something like 18% of the beam power is lost from the main beam into a forward cone of 30° half angle. This requires water cooling on shielding, collimators, target boxes, etc., as well as radiation hardening and remote maintenance capabilities. As an example of the radiation levels encountered, when the second target cell is opened exposing the main beam line, the radiation level ~20 ft above the beam line is 400 mr/h. This will increase by another factor of 30 after extended operation at the 1-mA level. Thus, even now we must do nearly all work remotely in target cells. In the long term the complexities of remote handling can only reduce the availability of the experimental area.

Experience thus far with radiation-cooled graphite targets has been good and they certainly should be appropriate for several hundred microamperes. Several years ago testing at low energies (high dE/dx) showed that slowly moving radiation cooled graphite should work at full current. In special cases where a particular geometry of production target is required water cooling may be needed.

Very accurate beam profiles are essential for control of the beam from target cell to target cell. Steering and focusing must be accurately adjusted on the basis of these profiles to minimize activation and to produce desired beam spots at the production targets. The instrument of choice for this work is a "harp" which is an assembly of parallel graphite wires crossing the beam. The secondary current induced by the beam is measured for each wire and displayed so that one-dimensional profiles are available at any time. Other harps provide the other dimension; appropriate bias fields are provided by additional planes of graphite wire. These devices make very nice beam displays; but, the maximum current density at which they can be used is unknown and any sudden vacuum failure will cause breakage of the harp wires.

The bulk shielding in the experimental halls is adequate for the 100-μA operation with typical working areas at 1 mr/h or less. Much of the radiation seen still comes from either cracks or lack of the requisite layer of hydrogenous material on some of the iron shielding. These defects are straightforward to cure so no major alterations are expected in the major shield as the current is increased. It is anticipated that roofs and modest increase in bulk shielding around the experimental caves will be required as the intensity is increased.

Plan for the Future

During the next year we expect to see the completion of our outstanding major experimental facilities and to operate at the 100-μA level for production. The outstanding experimental facilities are the High Resolution Spectrometer (HRS), the Isotope Production and Radiation Damage Facility, (ISORAD), the pion spectrometer, (EPICS) and the pulsed neutron facility. Construction of the HRS is complete and early tune-up has been started; it is anticipated that the experimental program using this device should start within the next few months. The ISORAD facility is essentially complete and

should also be in routine use within the next few months. The pulsed neutron facility should be ready for use by sometime in 1977. The proton beam line for the pulsed neutron facility is ~150-m long with both horizontal and vertical bends; beam has been sent through the more complicated portion of this transport system. The EPICS spectrometer is in the late assembly stages and it is anticipated that it shall be ready for experiments by May 1977. A 20-nA polarized proton beam will be available in early 1977 for use in Areas B and C.

We maintain a deep respect for the 80 W of average power in the 100-μA beam and the possibility of either unexpected thermal or radiation damage problems associated with such an intense source. We feel that it is essential that we gain a large amount of experience at this level before routine operation at higher currents is attempted. The experimental program has much the same flavor in that a certain amount of experience has to be gained before fully effective use of the higher intensities is possible. Thus our planned year of operation at 100 μA is appropriate from both development and production requirements.

During this year of 100-μA operation we shall be developing our resources so that we may go on to the next level of current (presumably three hundred microamperes) in a timely manner. In the experimental area much of the development work will be directed by what transpires in the target cells during this time. It is clear that we must strongly pursue effective methods of remote maintenance. We believe that all components within the target cells are accessible to remote handling; the time required for repair work is very dependent on the sophistication of the manipulators and viewing systems. We are pursuing such advanced devices as force feedback manipulators in an effort to make this work as cost effective as possible.

Another major concern in the experimental area is the system of beam instrumentation. The present harp system and current monitor system seems to be adequate at the 100-μA level; lifetime of components and the capabilities of the present system at higher currents requires exploration.

Along the accelerator a continual effort is maintained on improvement of stability of components and improved instrumentation. As examples of this work a redundant phase monitoring system is being installed on the entire machine, an improved momentum analysis system is going into the switchyard, a nonintercepting beam position monitor system will be installed in the next few months, and the stability of the resonance controllers on the accelerator tanks is being improved.

The major effort in the accelerator development work is a critical evaluation of the beam quality as current is increased. Some of the present areas of exploration are emittance damping along the machine, effect of relatively small changes in the accelerating field in the low-energy portion of the machine, control behavior of the rf system at higher currents, ion source properties, causes of beam halo and so on. These studies require very careful experimental work and frequently involve detailed beam dynamics calculations to interpret the results. This work is time consuming and re-

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- quires diligent attention to make progress. As yet, no indication of any insurmountable problems have been seen which would preclude eventual operation at higher currents.

The alignment of the machine remains a continuing problem which is exacerbated by the need for simultaneous acceleration of both positive and negative ions. Over much of the machine the alignment is apparently satisfactory; however, some problems remain in the region between the injectors and the first (100 MeV) part of the side-coupled accelerator.

Conclusion

LAMPF is a successful facility serving a wide variety of users at the 10⁻⁷-uA level. The availability of beam is satisfactory and a very large amount of scientific and applied investigation can be carried out with the facility in its present form. The engineering and applied physics problems in increasing the current another factor of ten are formidable but seem amenable to eventual solution.

Speculation

For the purpose of this conference it is interesting to raise the question of what will happen if the beam quality deteriorates much faster than expected as the current is increased. At worst, such deterioration will be in the form of excessive beam halos or an undue low-energy tail in the energy distribution. It is possible to increase the acceptance of the high-current beam line through the switchyard. In addition, collimators can be placed along the accelerator and in the switchyard in such a manner as to maintain our maintenance capability as well as the two-beam capability.

Acknowledgement

By this time many hundreds of people have worked on LAMPF. Without their imagination, skill and hard work this facility would not be possible.

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